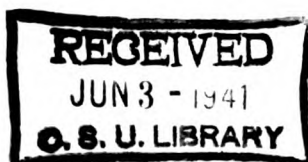


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UTILIZATION OF MANGANESE IN THE STEEL INDUSTRY



BY

B. A. ROGERS

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INFORMATION CIRCULAR

UNITED STATES DEPARTMENT OF THE INTERIOR - BUREAU OF MINES

UTILIZATION OF MANGANESE IN THE STEEL INDUSTRY^{1/}

By B. A. Rogers^{2/}

The problem of obtaining enough manganese for use in the manufacture of steel appears likely to recur when international relationships are disturbed and to become serious at any time when the United States is cut off from its customary supply. Some idea of the problems that arise under war conditions may be obtained from a description given by Ellicott^{3/} in 1918 before the American Iron and Steel Institute. This condition arises because in normal times there is an economic advantage in importing available high-grade foreign ores to the neglect of our own less satisfactory resources. That considerable low-grade manganese ore and a much smaller amount of high-grade material are available in this country is well known from geological surveys^{4/} and has been confirmed by Bureau of Mines investigations.^{5/} Locations of the various deposits are indicated in figure 1. The possibility of greatly expanding domestic production was actually demonstrated from 1913 to 1918, when the annual production of manganese from domestic ores rose from about 4 percent to approximately 35 percent^{6/}, ^{7/} of the total consumption of ferromanganese and spiegeleisen. An idea of how domestic production compares with total consumption in the United States can be obtained from figure 2, taken from the Minerals Yearbook^{8/} for 1939. Assuming that it is possible to increase production of manganese ores sufficiently to supply all our needs, such a program presumably would require 2 or 3 years, and the cost of production would certainly rise considerably, for some time at least. For

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- 1/ The Bureau of Mines will welcome reprinting of this paper, provided the following footnote acknowledgment is used: "Reprinted from Bureau of Mines Information Circular 7162."
 - 2/ Supervising engineer, Metallurgy of Steel Section, Metallurgical Division, Bureau of Mines.
 - 3/ Ellicott, C. R., The Conservation of Manganese: Am. Iron and Steel Inst. Yearbook, 1918, pp. 25-37.
 - 4/ Healey, M. V., and Johns, A. L., Selected Bibliography and Map of Manganese Deposits of the United States by Districts: Bureau of Mines Inf. Circ. 6274, 1930, 19 pp.
 - 5/ Dean, R. S., DeVaney, Fred D., and Coghill, Will H., Manganese: Its Occurrence, Milling, and Metallurgy, Part I: Bureau of Mines Inf. Circ. 6768, 1934, 98 pp.
 - 6/ Hewett, F. F., Manganese and Manganiferous Ores: Mineral Resources of the United States, part 1, 1918, pp. 607-656 (see p. 639).
 - 7/ Ridgway, Robert H., and Davis, H. W., Manganese and Manganiferous Ores: Minerals Yearbook, 1939, pp. 577-592 (see p. 579).
 - 8/ Ridgway, Robert H., and Davis, H. W., Work cited (footnote 7), p. 578.

these reasons it has become important to conserve manganese, and the suggestions that have been made for reducing the amount required may well be reviewed.

REASONS FOR USING MANGANESE

Manganese is used in steel for two reasons: First, because of its favorable effect on workability, and second, for its ability to improve the product. Good workability enables the steel to undergo forging, rolling, and other processes in the producer's plant without being torn or otherwise damaged. Improvement of the product refers to the ability of the steel to perform satisfactorily under various operations after it leaves the manufacturer's plant and in ultimate use. To these two reasons Ellicott,^{9/} with mild and not unreasonable sarcasm, added a third - the meeting of specifications that demand higher percentages of manganese than are necessary to give suitable properties to the finished product.

The beneficial effect of manganese in the reduction of ingots to the desired shape is well-known, and the general reasons therefor are fairly well agreed upon, although there is some controversy as to details. The action of manganese in taking the sulfur away from ferrous sulfide to form manganous sulfide appears to be of major importance. The nature of the first of these sulfides is such that at a certain stage of cooling it works out between the grains of steel^{10/} and surrounds them with thin, low-melting envelopes of iron sulfide; whereas the second agglomerates into small globules dispersed throughout the metal. A piece of steel which contains iron sulfide tends to fall apart during forging because of the lack of cohesion between the grains of metal, whereas one in which the sulfur is present as manganese sulfide does not exhibit this undesirable behavior.

The above paragraph does not completely explain why manganese eliminates the hot shortness of steel and permits it to be rolled without difficulty. There is little doubt that the amount of oxygen present also has an effect, and some investigators, particularly in Germany, consider it to be the major influence. A recent rather comprehensive experimental investigation and analysis of published data by Norris^{11/} resulted in the conclusion that a

^{9/} Ellicott, C. R., Work cited (footnote 3).

^{10/} Some evidence obtained by Urban and Chipman (Urban, Stephen F., and Chipman, John, Nonmetallic Inclusions in Steel: Trans. Am. Soc. Metals, vol. 23, 1935, pp. 645-671) and also Wohrman (Wohrman, C. R., Inclusions in Iron: Trans. Am. Soc. Steel Treat., vol. 14, 1928, pp. 81-126, 255-299, 385-414) indicates that ferrous sulfide lies in the boundaries between the original dendrites but does not have a very definite relationship to the boundaries of the ferrite grains.

It may be noted that in commercial steels the sulfides usually have some oxides associated with them. For example, iron sulfide is combined with a considerable proportion of iron oxide.

^{11/} Norris, Frank G., Factors Affecting Red-shortness: Jour. Iron and Steel Inst., vol. 138, 1938, pp. 75P-89P.

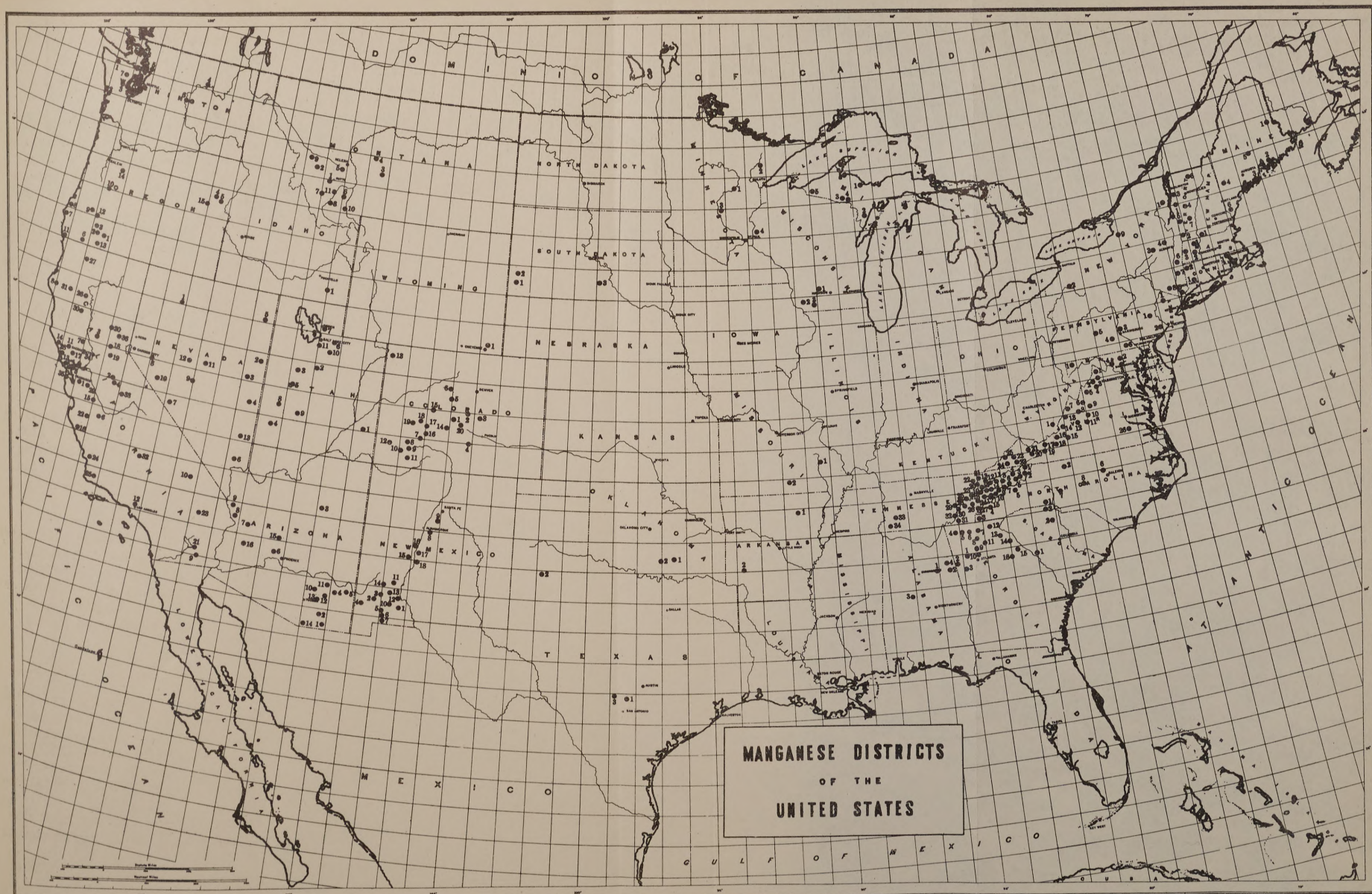


Figure 1.—Locations of the better known manganese deposits in the United States.

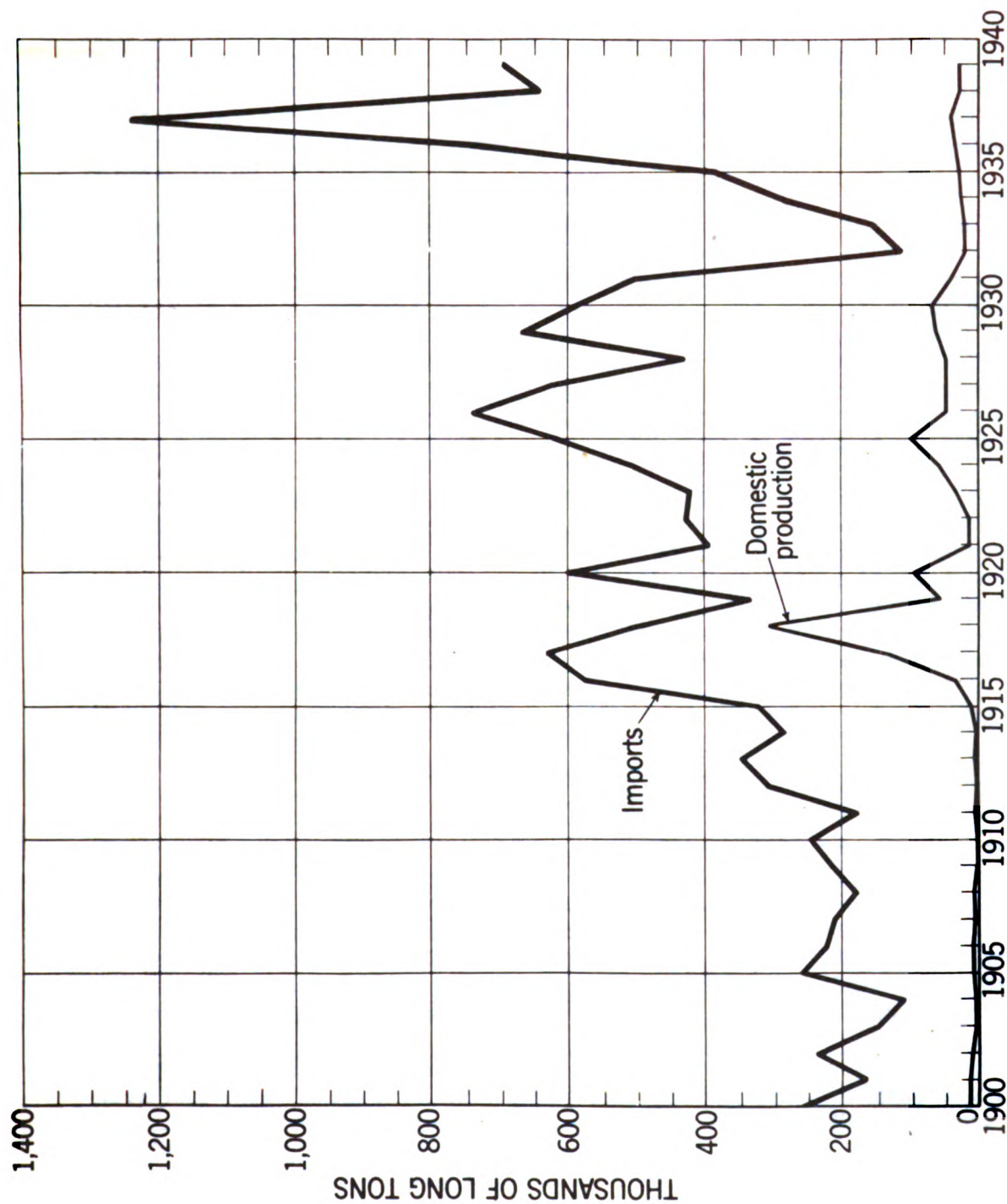


Figure 2.— Relative amounts of imported and domestic ore consumed from 1900 to 1939, inclusive. (Ore contained 35 percent or more manganese.)

steel in which the percentages of oxygen and sulfur are such that the ratio

$$\frac{\text{Mn} + 0.048}{\text{S} + 0.130}$$

is greater than 6.63 is never red-short; if this ratio is less than 3.30 the sample is always red-short; and if its value is intermediate the heat treatment of the sample determines the existence of the red-short condition. In this expression the chemical symbols represent the weight percentages of the corresponding elements.

The second reason for using manganese obviously refers to its employment as an alloying element. Manganese is commonly used in steels to impart certain properties desired by the fabricator or the ultimate consumer, but the product is not considered an alloy steel until the content of this element reaches 1.65 percent.^{12/} An example of such use is the addition to low-carbon sheet steel of 0.20 percent more manganese than the 0.15 to 0.20 percent required to insure good behavior in rolling. The additional amount eliminates the likelihood of the so-called "orange-peel" surface after a drawing operation and thus improves the quality of the finished product.

The two reasons outlined - to insure proper ductility under hot working at all temperatures and to improve the character of the steel for specific purposes - constitute the arguments for using manganese. They are not the only reasons, however, as the presence of manganese oxide in the furnace slag must be considered during melting operations, so that a difference in the amount of manganese charged presumably demands somewhat changed procedures in handling the furnace. Because of the lack of agreement concerning the function of manganese in the furnace this matter will not be considered further.^{13/} References to this subject may be found in recent articles by Lawrie,^{13/} Diepschlag,^{14/} and others.

CONSUMPTION OF MANGANESE

The total consumption of manganese in the steel industry can be estimated reasonably well, but knowledge of the amounts consumed in the various ferrous products is less accurate. It is particularly difficult to specify how much material is used to make rolling possible and how much is employed to improve the character of plain carbon steels. A rough idea may be gained by noting the approximate amount of manganese used in all classes of steel and arbitrarily assigning some fraction as being essential to insure proper

^{12/} This figure is an arbitrary one but has been adopted by the American Iron and steel Institute and is accepted by the industry generally. See American Iron and Steel Institute, Steel Products Manual, sec. 9: New York, July 1940.

^{13/} Lawrie, W. B., The Refining of Metal in the Basic Open-hearth Furnace: Jour. Iron and Steel Inst., vol. 139, 1939, pp. 257F-280P.

^{14/} Diepschlag, E., Das Mangan in der Stahlerstellung (Manganese in the Manufacture of Steel): Metallwirtschaft, vol. 17, 1938, pp. 1299-1302.

rolling characteristics. Probably because so often more manganese is added in greater quantities than will just suffice to insure suitable working properties in the manufacturer's plant, little information is available as to the minimum amount necessary for this purpose. Furthermore, the percentage is not the same in all plants. A modern mill with first-class heating equipment can roll material containing slightly less manganese, other factors remaining the same, than can be handled with an older type mill with poor heating arrangements. As the present problem primarily concerns the consumption of manganese-containing addition substances, estimates of amounts used will refer only to the manganese added at the end of the heat.

A rimming steel may be rolled consistently if it contains 0.18 percent manganese^{15/} or perhaps even a little less in some cases. Since the residual manganese in a heat of such steel may be approximately 0.10 percent, probably 0.08 percent must be added as a minimum. On the other hand, for some types of killed steels addition of 0.25 percent manganese above the residual amount may be desirable. For all classes of steel an average (which, it should be emphasized, is only a very rough estimate) of 0.15 percent will be assumed. In 1937 the total output of steel ingots was slightly more than 50,000,000 gross tons.^{16/} In view of the above assumptions the round number is accurate enough for the purpose. On this basis 75,000 tons of manganese was required to make this quantity of steel workable.

The total amount of manganese consumed in the form of ferromanganese and spiegeleisen in 1937 was, in round numbers, 350,000 long tons,^{17/} of which approximately 320,000 tons was furnished by ferromanganese and the remainder by spiegeleisen.^{18/} The assumption of an average loss of 25 percent^{19/} in making the additions indicates that about 265,000 tons of manganese actually entered the steel. Of this total amount, about 75,000 tons, or about 28 percent, was used in making the steel workable. If this conclusion is put in round numbers, the analysis indicates that somewhat less than

^{15/} No manganese at all is added to Armco ingot iron and low metalloids heats in general. Furthermore, such heats contain very little residual manganese. They are rolled in a rather special way to avoid trouble from hot-shortness.

^{16/} Ridgway, Robert H., and Davis, H. W., Iron Ore, Pig Iron, Ferro-alloys, and Steel: Minerals Yearbook, 1938, pp. 479-523 (see p. 519).

^{17/} Ridgway, Robert H., and Davis, H. W., Manganese and Manganiferous Ores: Minerals Yearbook, 1938, pp. 525-539.

^{18/} Apparently some 75,000 long tons of manganese was also contributed by high-manganese iron ores used in making pig iron, since, according to the Minerals Yearbook (p. 536) 1,189,000 long tons of domestic ore containing 5 to 10 percent manganese and 830,000 long tons of domestic ore containing 2 to 5 percent manganese were shipped during that year. Probably some of the pig iron made from this ore was used in recarburizing steel, but the major portion was in iron charged into steel furnaces.

^{19/} Some metallurgists with whom the point has been discussed believe this estimate is too low and that the loss should be stated as 30 percent or even more. The rounded figures mentioned later in the paragraph actually correspond to a slightly higher loss.

one-third of the manganese is used for the benefit of the producer of steel and a little more than two thirds in improving the character of the steel for the benefit of the user.

Relatively little manganese is consumed in products classed as alloys. In this group may be put, besides the steels containing more than 1.65 percent manganese, Hadfield steels (11 to 14 percent manganese) and cast steels and cast irons containing added manganese. This group is not large and for practical purposes may be ignored, as it probably does not consume more than 4 or 5 percent of the manganese used in the steel industry. The consumption of manganese in Hadfield steels, for example, may not have exceeded 5,000 tons in 1939.

MANGANESE-CONTAINING PRODUCTS NOW USED OR AVAILABLE TO THE INDUSTRY

Various manganese products are available for use in deoxidation work. For conciseness these are listed below in the order of their manganese content:

1. Electrolytic manganese and manganese metal (95 to 98 percent manganese).
2. Ferromanganese (and silicomanganese).
3. Spiegeleisen (and silicospiegel).
4. Manganiferous pig iron.

Electrolytic manganese is a recent product^{20/}, ^{21/} with an actual manganese content probably in excess of 99.9 percent and with practically no phosphorus and very little sulfur. Fortunately it can be made from relatively low-grade ores, but at present production is not on a scale to furnish large amounts to the steel industry. So far the cost of the material has been somewhat higher than an equivalent amount of manganese in the ferro-alloy form. Whether, in event of restricted imports and resulting rise in prices for other varieties and lowered costs incident to larger-scale production, the situation might change cannot be predicted now. Experiments by the Jones & Laughlin Steel Corporation have indicated that the electrolytic product behaves essentially the same as ferromanganese in open-hearth steel.^{22/} Use of this product would logically be in the comparatively small tonnage of

^{20/} Shelton, S. M., Royer, M. B., and Towne, A. P., Progress Reports - Metallurgical Division, 23. Electrometallurgical Investigations, Electrolytic Manganese: Bureau of Mines Rept. of Investigations 3406, 1938, pp. 3-16.

^{21/} Hammerquist, William L., Electrolytic Manganese, A New Metallurgical Raw Material: Steel, vol. 105, No. 18, October 30, 1939, pp. 42-45.

^{22/} Banta, H. M., Comparison of Electrolytic Manganese with the Regular Ferro Grades for the Production of S. A. E. 1035 Steel: Jones & Laughlin Steel Corporation, Research and Development Div., Rept. 90-40, 1940, 6 pp.

low-carbon, high-manganese products, where it would have an economic advantage because of the furnace time saved in not having to reduce the carbon in the heat to compensate for that added with the ferromanganese.

Manganese metal containing 95 to 98 percent of the element is a thermite product that hitherto has been unable to compete economically with ferro manganese. The commercial product contains about 1 percent of either silicon or aluminum, or both.

Ferromanganese is an alloy of approximately 80 percent manganese with about 16 percent iron and carbon up to about 6 or 7 percent, depending on the method of production. It is the material usually made from high-grade manganese ores or concentrates that, for the most part, are imported, and it is probably the most convenient form in which to add manganese. To avoid the addition of carbon to low-carbon, high-manganese steels an electric-furnace product containing much less carbon than the usual blast-furnace alloy is sometimes used. However, consumption of the former substance is small. Its cost is perhaps twice as great as that of the alloy made in the blast furnace. For certain killed steels silicomanganese with the approximate composition 65 to 70 percent manganese, 12 to 25 percent silicon, and 1.2 to 2.5 percent carbon is preferred. Ferromanganese has the distinct advantage over other forms of manganese alloys that considerable percentages of manganese (perhaps as much as 1.5 percent) can be introduced in the ladle without cooling the steel excessively. It is of interest to note that during the first World War the manganese content of ferromanganese was permitted to drop as low as 60 percent.

Spiegeleisen is the other form of alloy commonly used for introducing manganese. It usually contains about 20 percent of the element (a 27-percent grade also is on the market), although in 1913 a product with as little as 16 percent was considered acceptable. The rest of the alloy consists of iron plus about 5 percent carbon and perhaps 0.5 percent silicon. The fact that about 148,000 tons was produced and imported in 1936 indicates its current use. At present much the larger proportion of spiegeleisen is made from domestic ores. Silicospiegel, which contains perhaps 25 to 30 percent manganese and 7 to 8 percent silicon, finds limited use in the industry.

Spiegeleisen is a satisfactory substitute for the ferro-alloy in making additions of manganese, provided that the accompanying elements, such as carbon and phosphorus, are consistent with the grade of steel being made. For example, spiegeleisen as a recarburizer for rail steel replaces pig iron as a source of carbon and ferromanganese as a source of manganese. Difficulty resulting from cooling the steel by too large an amount of cold spiegeleisen either in the furnace or in the ladle may be avoided by preheating or premelting the added material.

The manganiferous pig iron with perhaps 5 percent manganese can be used for additions when the amount required is not too great or may be supplemented by the use of ferro manganese. For additions in the ladle this substance may be used in the molten condition.

METHODS OF ECONOMIZING IN THE USE OF MANGANESE

A variety of schemes have been presented for reducing the amount of manganese required for the production of satisfactory steel. These suggestions may be divided into the following classes:

- a. Economy in use of amount of manganese.
- b. Economy in use of high-grade manganese by substitution of low-grade material.
- c. Substitution of other deoxidizing agents.
- d. Substitution of other substances, such as nickel or chromium, for strengthening agents.
- e. Furnace procedures designed to reduce the amount of material needed.

Item a is intended primarily to cover the consumption of manganese in steel used for purposes for which material of lower quality would serve equally well. In other words, it refers to the manganese used to meet specifications. The amount involved at present is probably considerably less than the quantity about which Ellicott^{23/} complained, but a survey of the uses to which certain products are put would probably result in some saving. The use of slightly higher carbon contents no doubt would offset the lower percentages of manganese in certain products without detriment to structures in which the material was used. Ellicott^{23/} suggested that when possible rimmed steel be substituted for the killed product as less manganese is required in the manufacture of the former. As the use of rimmed steels has expanded considerably in recent years the opportunities for saving manganese by this substitution are limited, but the point is worth remembering.

The methods of economizing included in item b evidently do not involve so much a saving in manganese metal as a change in practice to make use of available material. During the first World War it was frequently necessary to substitute spiegeleisen for ferromanganese. Furthermore, manganiferous pig iron was often substituted for spiegel in recarburizing work.^{23/}

Most recently Herty^{24/} proposed use of a silicon-containing spiegeleisen of the composition 20 percent manganese, 4 percent silicon, 4.25 percent carbon, and the remainder iron and also of a special alloy containing 30 percent manganese, 5.5 percent silicon, and 2.5 percent carbon, both of which can be manufactured from ores available in this country. Such agents could not be used for all types of steel but could replace a large proportion of the ferromanganese and silicomanganese now being used. The heat of reaction of the silicon present in this alloy should compensate somewhat for the

^{23/} Ellicott, C. R., Work cited (footnote 3).

^{24/} Herty, C. H., Jr., A Practical Method of Solving the Emergency Manganese Problem: Bureau of Mines Rept. of Investigations 3107, 1931, 7 pp.

chilling effect of the addition and permit its use in the cold condition in greater quantities. Furthermore, because of the action of silicon on the oxygen in the bath the losses of manganese should be less than for ordinary spiegeleisen. An estimate of the potential tonnage of spiegeleisen of this type that could be obtained from the Cuyuna district was calculated by Herty from data published by Joseph, Barrett, and Wood.^{25/} This information is repeated here as table 1.

TABLE 1. - Potential spiegel production from Cuyunal ores

Group	Potential tonnage of spiegel	Analysis of spiegel, percent			
		Mn	P	Fe	C ^{1/}
<u>Black ores:</u> ^{2/}					
1.....	1,023,000	19.17	0.13	76.20	4.5
2 A.....	352,000	31.95	.18	63.37	4.5
2 B.....	208,000	30.90	.30	64.30	4.5
3.....	165,000	29.19	.31	64.20	4.5
Total and weighted average.....	1,748,000	23.97	.18	71.35	4.5
<u>Brown ores:</u>					
2 C.....	6,430,000	14.07	.53	80.90	4.5
3 A.....	738,000	16.26	.29	78.95	4.5
3 B.....	1,185,000	16.85	.48	78.17	4.5
3 C.....	118,000	16.79	.66	78.05	4.5
4.....	175,000	22.64	.39	72.47	4.7
Total and weighted average.....	8,546,000	14.90	.50	80.10	4.5

^{1/} Assumed carbon content.

^{2/} Includes only ores containing less than 20 percent silica.

As may be seen from this table, the ores in the Cuyuna district alone are sufficient to provide manganese alloy of these grades for a considerable period.

In discussing item c, relating to the substitution of other deoxidizing agents, the point may well be emphasized that manganese is more important for its ability to render ineffective the bad characteristics of sulfur in rolling and forging operations than for its deoxidizing power. There are a number of agents, of which silicon is an example, that are more effective deoxidizers than manganese. However, silicon is not a substitute for manganese because it does not remove the harmful effects of sulfur. Of the various substitutes that have been reported, zirconium and titanium appear to have the greatest possibilities.

^{25/} Joseph, T. L., Barrett, E. P., and Wood, C. E., Minnesota Manganiferous Iron Ores in Relation to the Iron and Steel Industry: Trans. Am. Inst. Min. Met. Eng., vol. 75, 1927, pp. 292-338.

A brief résumé of investigations relating to the production of steels containing zirconium appeared some time ago in an editorial in *Metal Progress*.^{26/} Feild^{27/} appears to have been the first to demonstrate that zirconium has a strong tendency to combine with sulfur. He concluded that zirconium formed a sulfide with the plastic properties of manganese sulfide, but Urban and Chipman^{28/} believe that simple zirconium sulfide forms angular inclusions. The latter authors did not dispute Feild's statements of satisfactory workability when zirconium was added. Ritchie^{29/} also found a beneficial effect on adding zirconium alloys to his rather special compositions.

Titanium (ferrotitanium, ferrocarbon titanium) is used in the metallurgical industry in a number of ways,^{30/} ^{31/} for example, in the production of non-aging sheet steel.^{32/} Like zirconium, it has a strong affinity for sulfur, oxygen, and nitrogen. Little has been published on the exact behavior of titanium with respect to sulfur. Information made available by F. G. Norris in a personal communication indicates that in certain types of steels satisfactory rolling properties can be obtained by the percent-for-percent substitution of titanium for manganese. Because of the vigorous reaction of titanium with oxygen the sum of the percentages of manganese and titanium ordinarily need not exceed 3.5 times the percentage of sulfur to give workable material.

From the purely technical point of view both zirconium and titanium appear to have some possibilities as substitutes for manganese, although both seem to be excluded for this purpose in rimming steels, as they would produce a killed steel before taking care of the sulfur. However, the cost of either ferro-alloy (which is not a serious matter in amounts in which they are generally used) would be high upon such a basis as point-for-point substitution for manganese. When this report was written, the cost per pound of contained zirconium was at least four or five times that of manganese, and titanium was somewhat more expensive. Another point to note in this connection is that present supplies of zirconium are predominantly imported and that part of the titanium also is of foreign (largely Canadian) origin. Domestic

^{26/} *Metal Progress*, Ductile Steel Made Without Manganese: Vol. 19, June 1931, pp. 69-70.

^{27/} Feild, Alexander I., Some Effects of Zirconium in Steel: *Trans. Am. Inst. Min. and Met. Eng.*, vol. 69, 1923, pp. 848-883. Effect of Zirconium on Hot-rolling Properties of High-sulfur Steels and the Occurrence of Zirconium Sulfide: *Trans. Am. Inst. Min. and Met. Eng.*, vol. 70, 1924, pp. 201-217.

^{28/} Urban, Stephen F. and Chipman, John, Work cited (footnote 10).

^{29/} Ritchie, S. B., Steels Made Without Manganese: *Metal Progress*, vol. 20, September 1931, pp. 35-39, 118.

^{30/} Comstock, George F., New Role of Titanium in Steels and Alloys: *Metal Progress*, vol. 27, January 1935, pp. 36-41.

^{31/} A number of references to very recent work are contained in a booklet by the Titanium Alloy Mfg. Co., *Titanium and Its Use in Steel*: Niagara Falls, N. Y., 1940.

^{32/} Hayes, Anson, and Griffis, R. O., Non-aging Iron and Steel for Deep Drawing: *Metals and Alloys*, vol. 5, 1934, pp. 110-112.

sources probably could supply the need for the latter element at some advance in price.

The substitution of other strengthening agents for manganese (item d) can be considered very briefly. The manganese used as an alloying element can obviously be replaced, with satisfactory results, by other elements, such as nickel, chromium, or silicon. However, as the manganese-containing steels have found use partly because they are less expensive than the low-alloy types the evidence points to continued use of manganese until its cost rises considerably. There seems little reason to doubt, however, that in an emergency such replacements could be made; but consideration should be given to the fact that chromium is also a strategic metal and that nearly the entire supply of nickel comes from Canada.

With respect to item e, dealing with the conservation of manganese in open-hearth-furnace operation, Kinney^{33/} commented on the fact, well known to steel men, that certain basic furnace procedures, particularly the employment of high-manganese pig iron or the addition of manganese in some other form to the charge, make possible retention of a high-residual manganese and thus reduce the amount of the ferro-alloy to be added at the end of the heat. The use of small slag volumes and delay in adding limestone were recommended for this purpose by Bardenheuer and Thanheiser.^{34/} Bardenheuer and G. Henke^{35/} have described a number of procedures in handling molten steel which they assert permit small savings of manganese; an example is the tilting of the ladle in such a way as to avoid turbulence as the steel is being run in. Other possibilities that might be considered are the reduction of sulfur in the pig iron (hot metal) by means of soda ash or some equivalent procedure and its elimination from the incoming fuel. The smaller amount of sulfur introduced into the furnace should require less manganese to render it harmless.

CONCLUSION

The above analysis indicates strongly the use of manganese alloys made from low-manganese ores as the most satisfactory method of compensating for an insufficiency of ferromanganese of customary grade. Reduction of the amount of manganese in the specifications is possible in some instances, but for the most part the change would involve either a lowering of the physical properties of the steel or the use of some deoxidizing or alloying substance

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- ^{33/} Kinney, C. L., Jr., Economic Significance of Metalloids in Basic Pig Iron in Basic Open-hearth Practice: Trans. Am. Inst. Min. and Met. Eng., vol. 70, 1924, pp. 136-170.
- ^{34/} Bardenheuer, Peter, and Thanheiser, Gustav, Wege zur Manganeersparnis beim Siemens-Martin-Verfahren (Methods of Saving Manganese in the Operation of Siemens-Martin Furnaces): Mitt. Kais. Wilh. Inst. Eisenforsch., vol. 20, 1938, pp. 67-75.
- ^{35/} Bardenheuer, P. and Henke, G., Vermeidung von Manganverlusten beim Siemens-Martin-Verfahren (Preventing the Loss of Manganese in the Open-hearth Process): Mitt. Wilh. Inst. Eisenforsch., vol. 21, 1939, pp. 243-260.

at least as expensive as manganese and perhaps more difficult to obtain. Furthermore, operation with decreased manganese would be likely to require some change in practice and perhaps involve some delay.